The CKM matrix and flavor physics from lattice QCD

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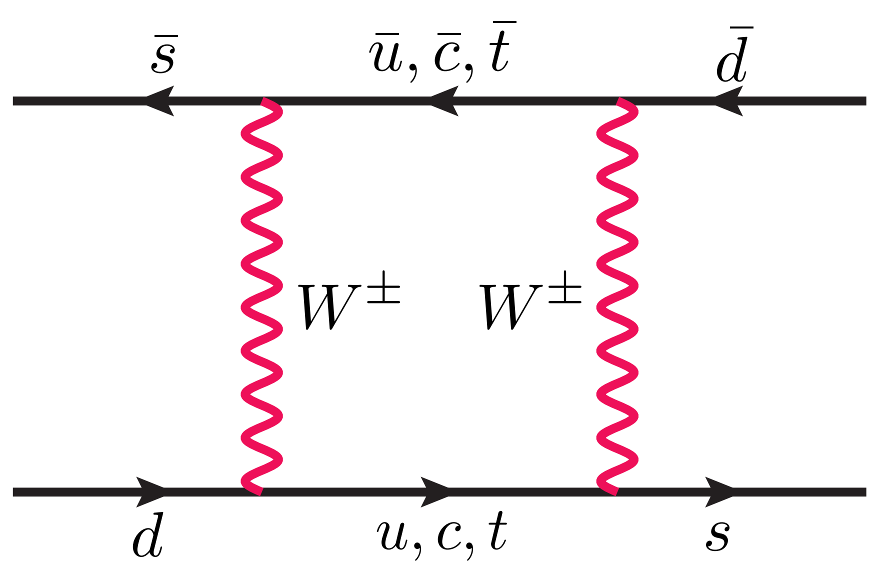
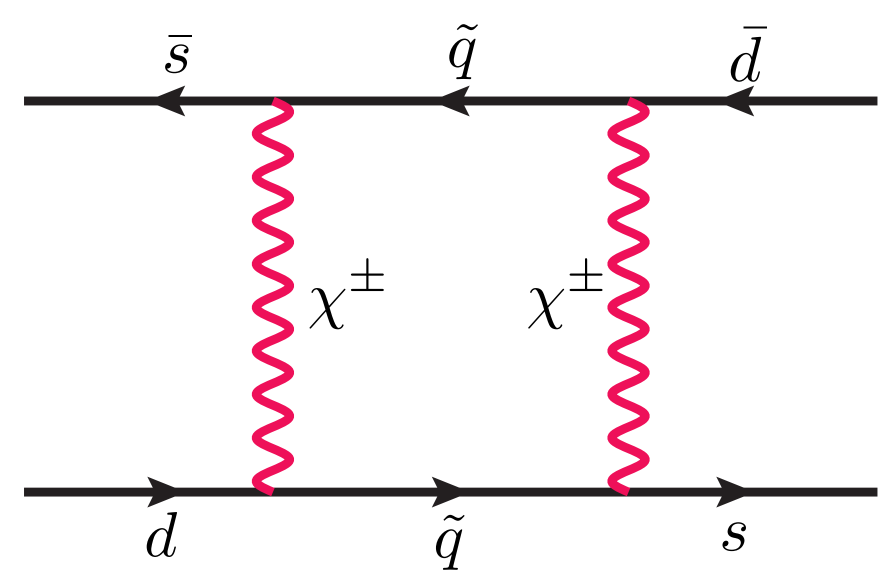
Why study flavor physics?

- Most extensions of the Standard Model contain new CP-violating phases and new quark-flavor changing interactions
  - $\Longrightarrow$ **We expect new physics effects in the quark flavor sector**
- The flavor sector is sensitive to physics at very high scales
  - New particles will typically appear in loop-level processes such as neutral kaon mixing:

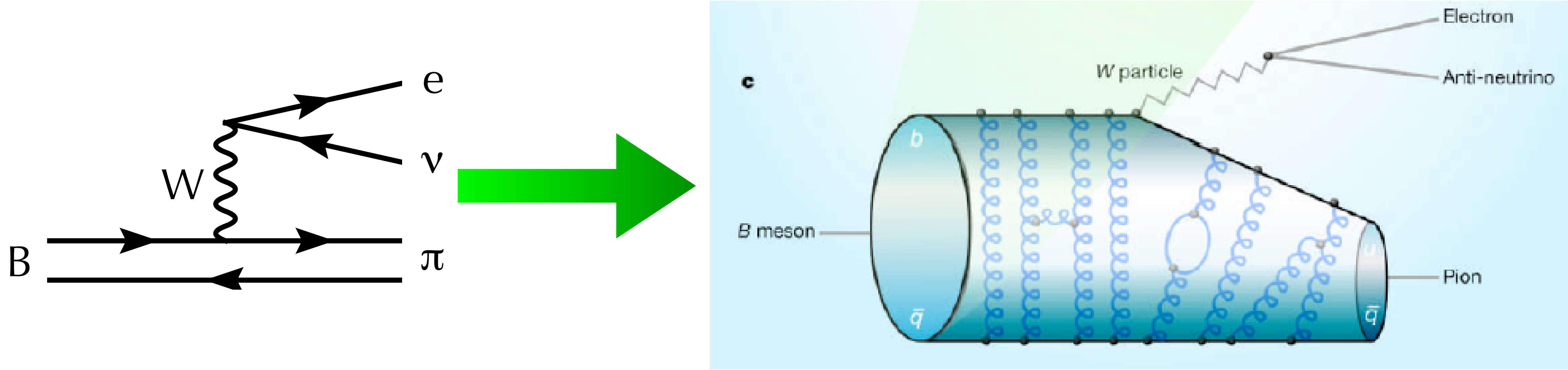




- $\Longrightarrow$ We may see evidence for new physics in the flavor sector before we produce non-Standard Model particles directly at the LHC!

Lattice QCD and precision flavor physics

- Experiments have been pouring out data to pin down the CKM matrix elements but lattice calculations are needed to interpret many of their results
  - Schematically, EXPT. = CKM × LATTICE
- In order to accurately describe weak interactions involving quarks, must include effects of confining quarks into hadrons:



- Typically absorb nonperturbative QCD effects into quantities such as decay constants, form factors, and bag-parameters which we must compute in lattice QCD
- **Precise lattice QCD calculations of hadronic weak matrix elements are critical to maximize the scientific output of the experimental high-energy physics program**

Lattice QCD constraints on the CKM matrix

- "Gold-plated" lattice processes allow the determination of most CKM matrix elements:
  - 1 hadron in initial state; 0 or 1 hadron in final state
  - Stable (or narrow and far from threshold)

$$\begin{pmatrix} \boldsymbol{V_{ud}} & \boldsymbol{V_{us}} & \boldsymbol{V_{ub}} \\ \pi \to l\nu & K \to \pi l\nu & B \to \pi l\nu \\ \boldsymbol{V_{cd}} & \boldsymbol{V_{cs}} & \boldsymbol{V_{cb}} \\ D \to l\nu & D_s \to l\nu & B \to Dl\nu \\ D \to \pi l\nu & D \to Kl\nu & B \to D^* l\nu \\ \boldsymbol{V_{td}} & \boldsymbol{V_{ts}} & \boldsymbol{V_{tb}} \\ \langle B_d|\overline{B}_d\rangle & \langle B_s|\overline{B}_s\rangle & \end{pmatrix}$$

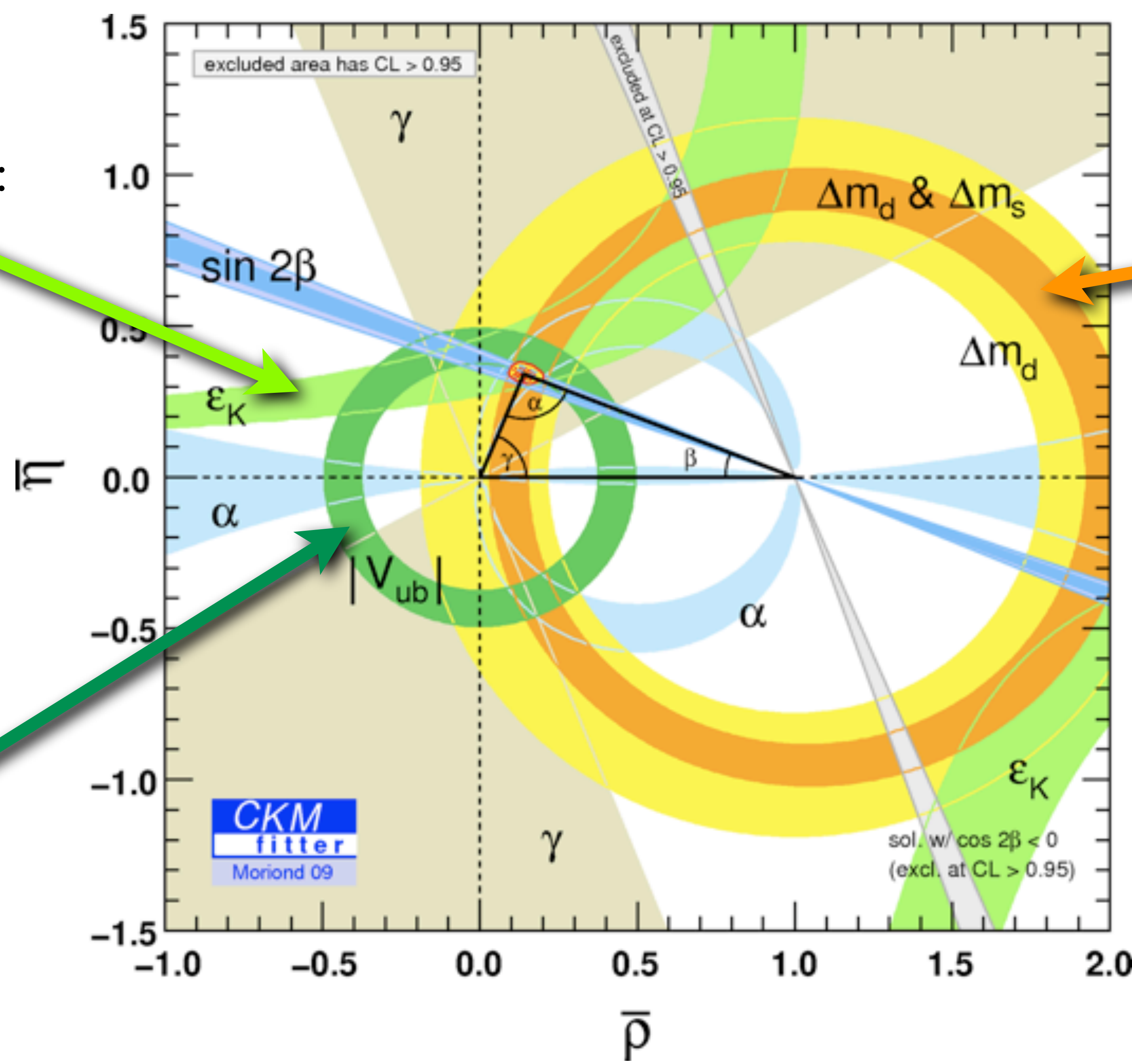
- Members of the BNL high-energy theory group are currently working on the quantities that are **circled in PINK**

Lattice QCD inputs to the unitarity triangle

- Many constraints on the unitarity triangle require lattice QCD calculations of hadronic weak matrix elements
- Members of the BNL high-energy theory group are currently computing **several key inputs**:

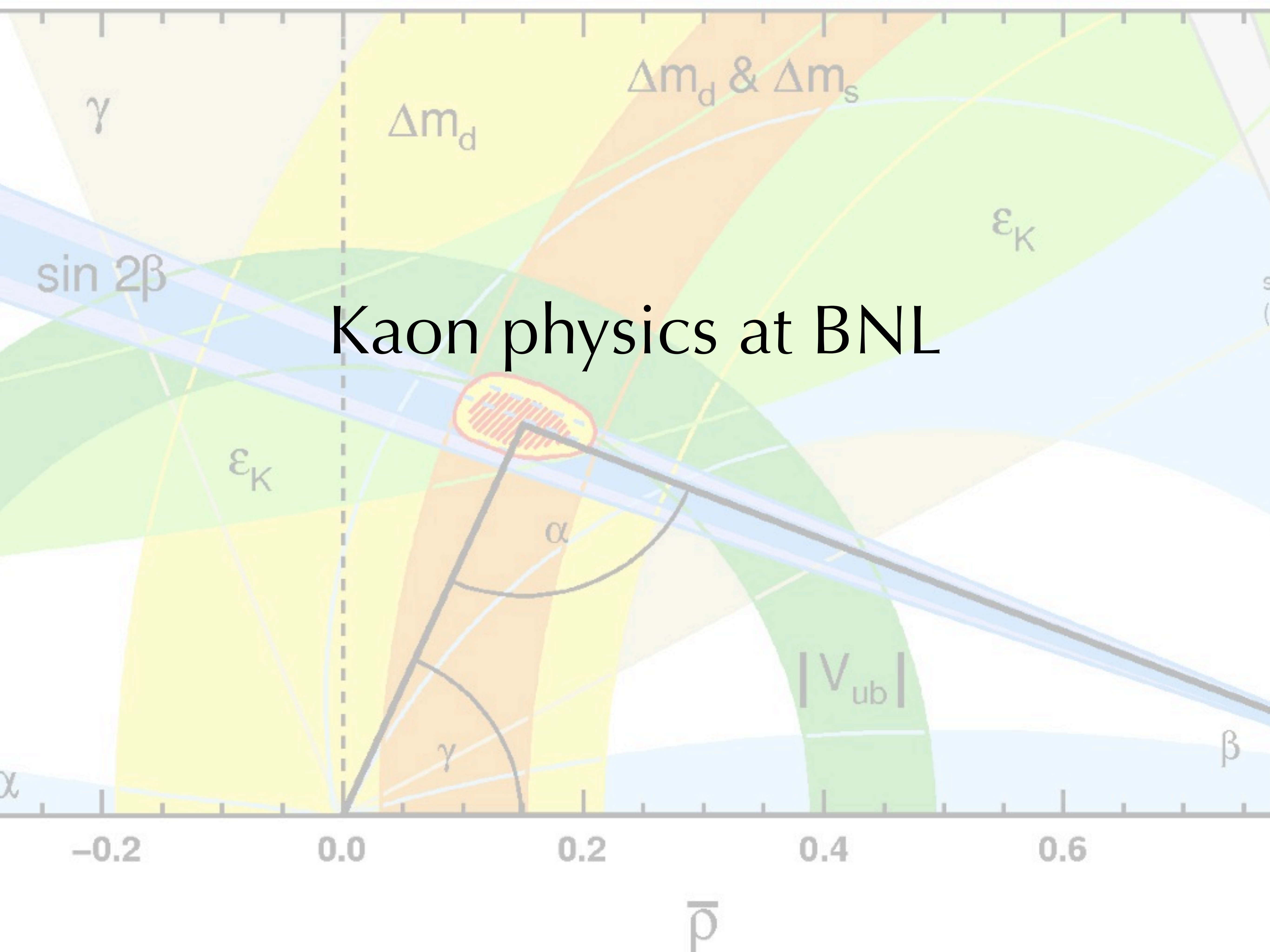
neutral Kaon mixing:
B_K

semileptonic
B-meson decays:
$f_+(q^2) \rightarrow |V_{ub}|$



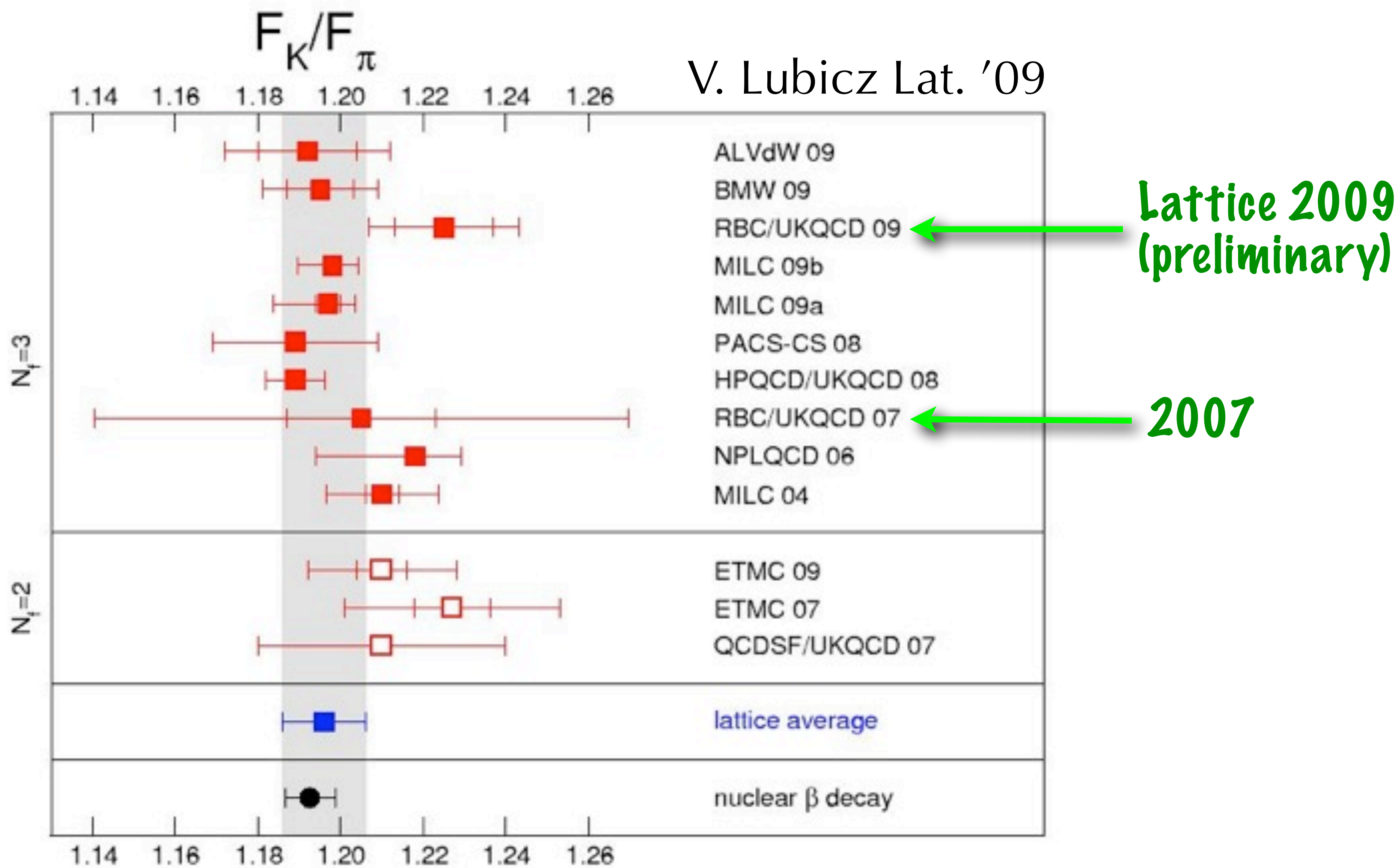
B-meson decays
and mixing:
f_B & B_B

Kaon physics at BNL



f_K/f_π (RBC/UKQCD)

- The ratio f_K/f_π allows a precise determination of $|V_{ud}|/|V_{us}|$ [**Marciano**]
- In the past year, RBC/UKQCD have added data at a second lattice spacing and reduced their errors significantly

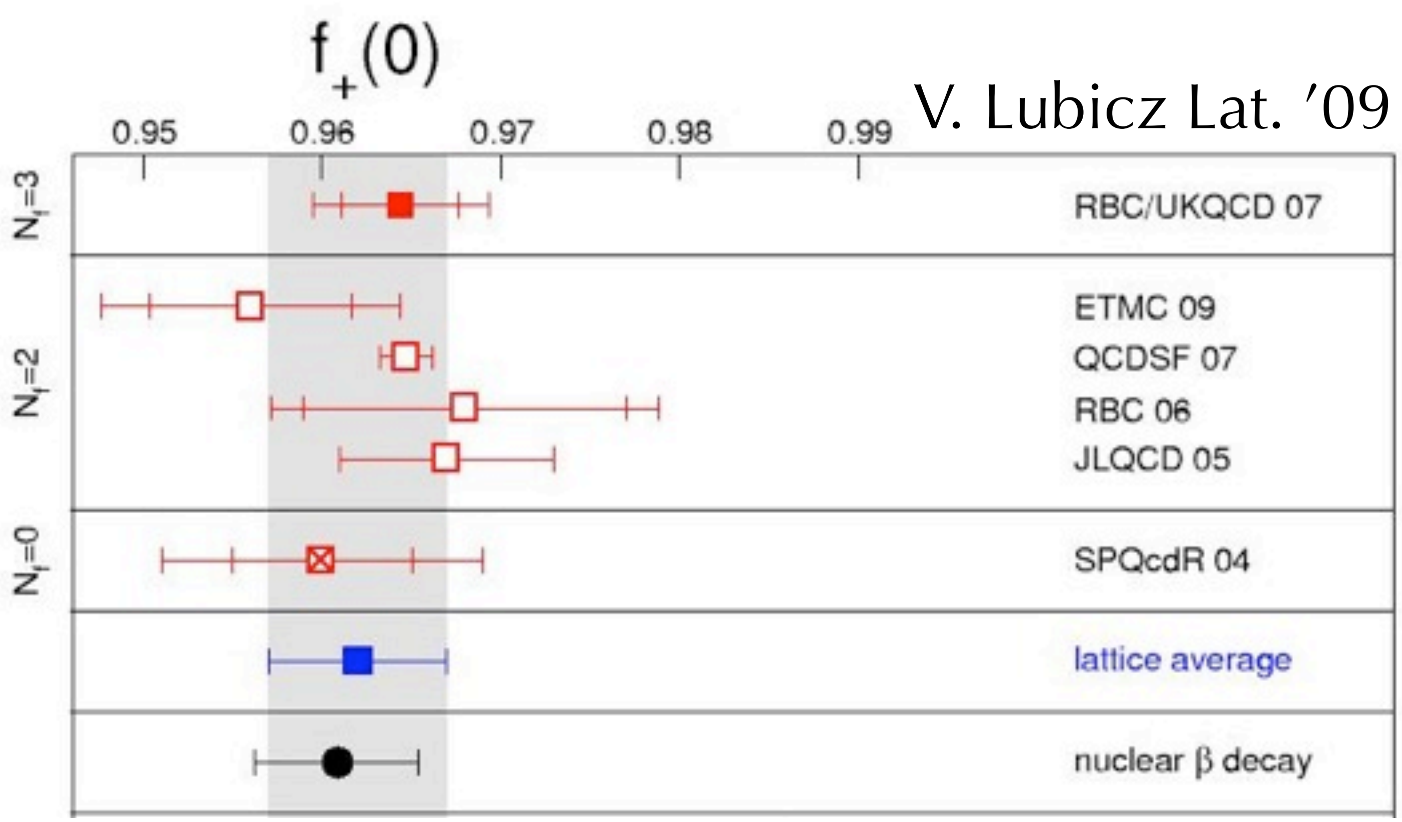


- *New preliminary result is competitive with other three-flavor lattice calculations*

$K \to \pi \ell \nu$ semileptonic form factor (RBC/UKQCD)

- Experiments measure the product of the form factor times the relevant CKM matrix element, **$f_+(0) \times |V_{us}| = 0.2166(5)$**, to 0.2% accuracy
  - $\Rightarrow$ Need lattice calculation of form factor to obtain $|V_{us}|$
- In 2008, the RBC/UKQCD Collaborations published the first realistic calculation of the $K \to \pi l \nu$ form factor which includes the effects of the u, d, and s "sea" quarks

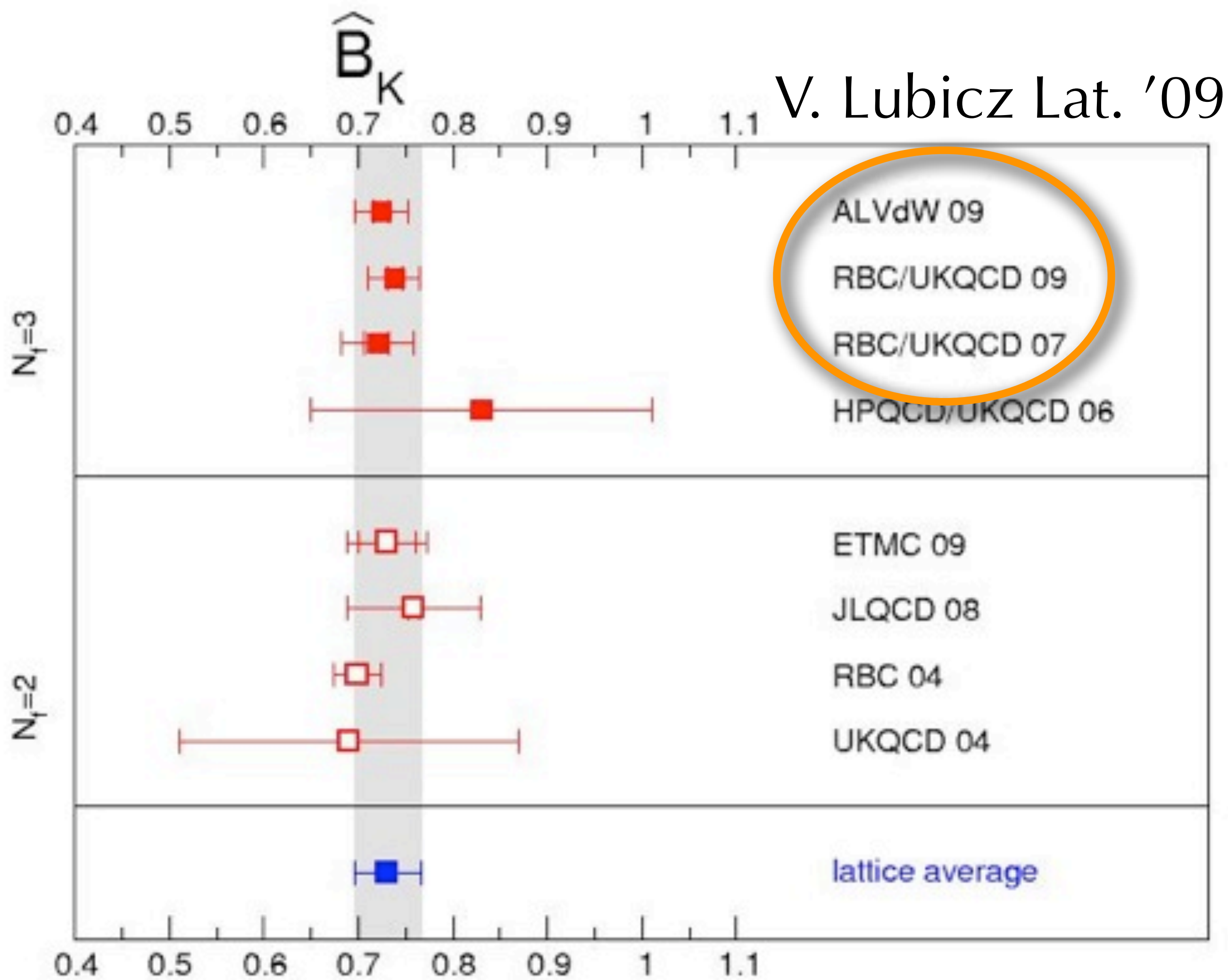
V. Lubicz Lat. '09



- *Leads to the current best determination of the CKM matrix element $|V_{us}|$ with a total error of 0.6%*

Neutral kaon mixing parameter B_K

- The amount of direct CP-violation in the neutral kaon system, ε_K, is known to sub-percent precision, and constrains the apex of the CKM unitarity triangle
- Until recently, the uncertainty in the ε_K band was primarily due to the uncertainty in lattice QCD calculations of the hadronic matrix element B_K



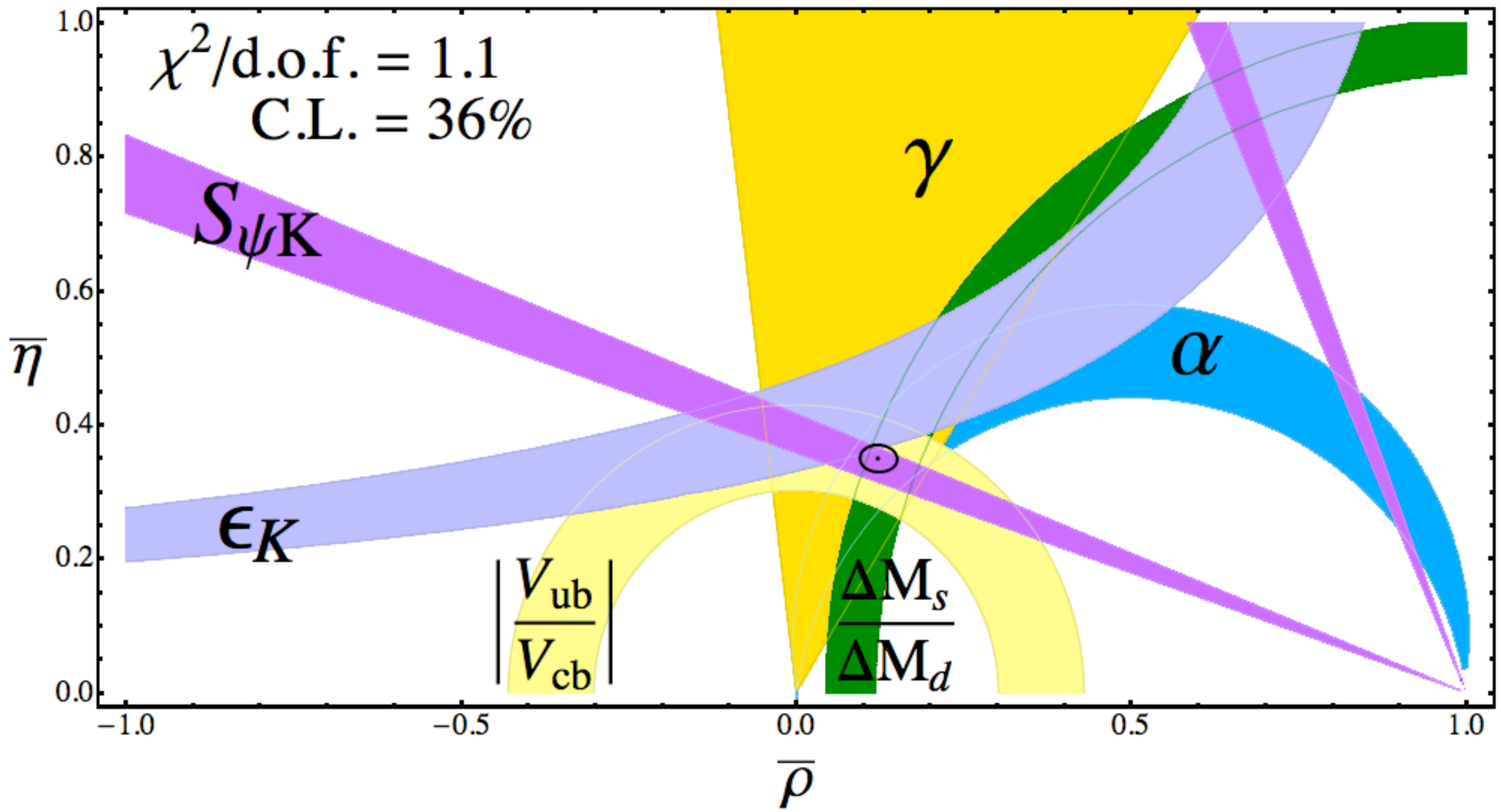
V. Lubicz Lat. '09

- 2007: RBC/UKQCD published the first precise three-flavor lattice calculation of B_K with a 6% accuracy
- May 2009: Aubin, Laiho, and RV obtained the first three-flavor lattice determination from data at two lattice spacings with a ~4% error
- The **independent result of ALVdW using a different lattice formulation confirmed that of RBC/UKQCD**
- Lattice 2009: RBC/UKQCD presented a preliminary result obtained from two lattice spacings with a reduced ~4% error

Status of B_K constraint on the unitarity triangle

- Given the improved recent lattice determinations of B_K there is a 2-3σ tension between the ε_K band and the other UT constraints [**Lunghi & Soni 2008**]

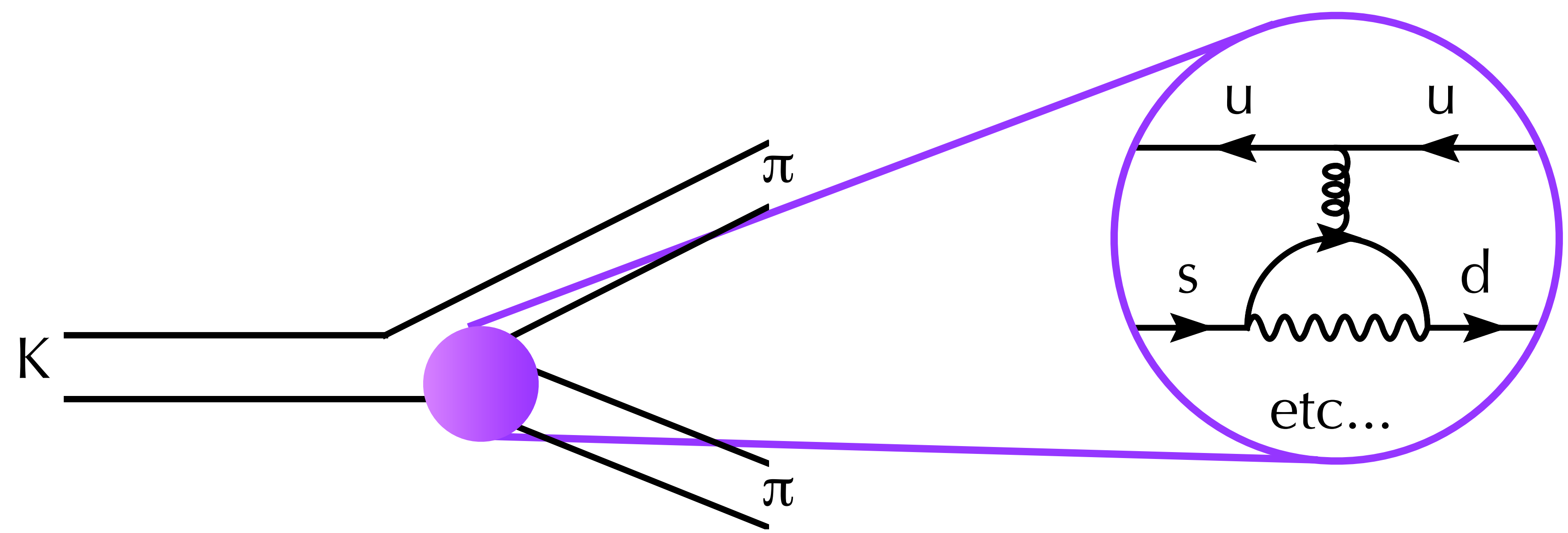
Laiho, Lunghi, RV in preparation



- May be a hint of new physics in neutral kaon mixing...

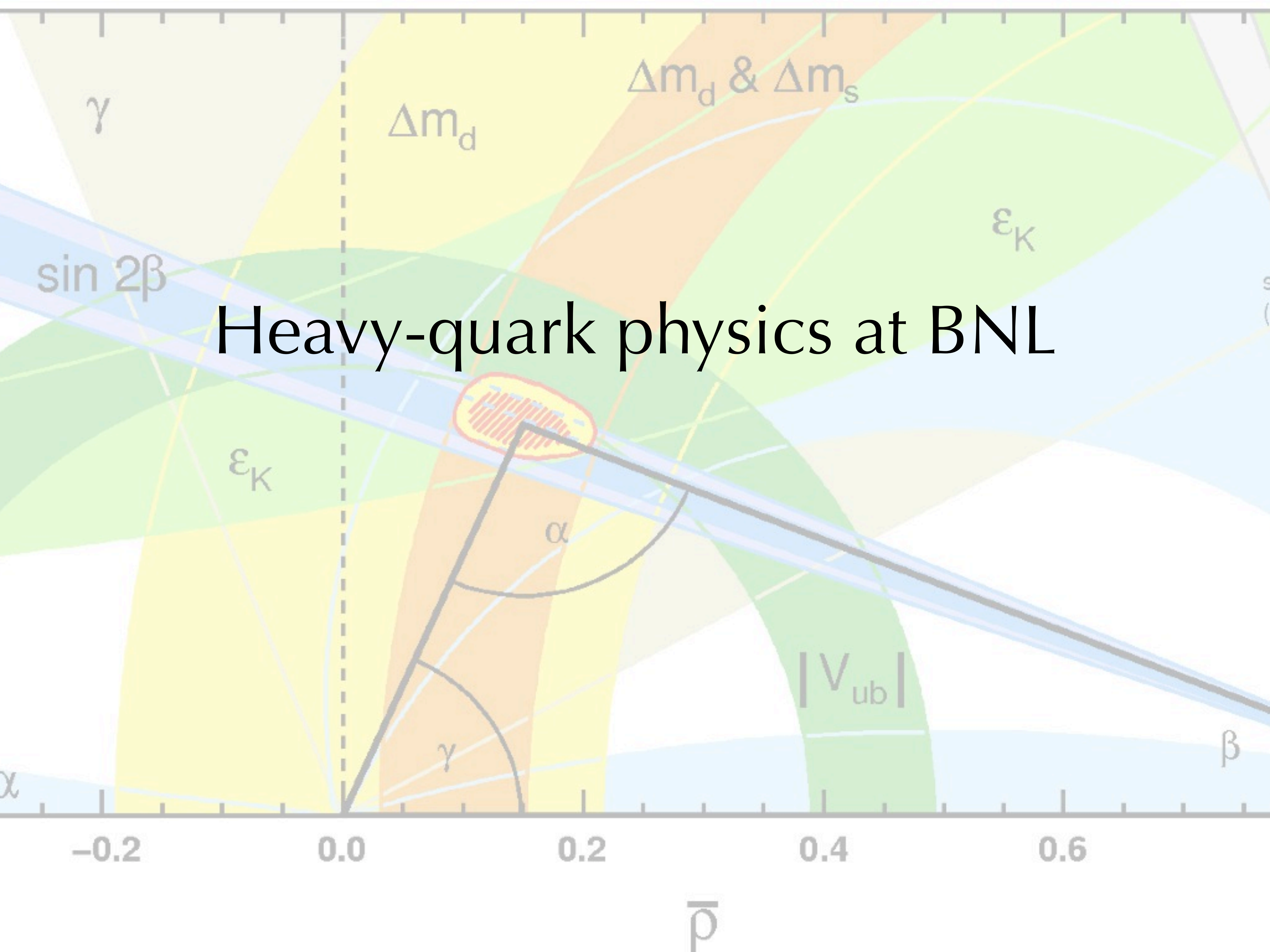
K→ππ decay (RBC/UKQCD)

- Origin of ΔI=1/2 rule ($A_2/A_0 \sim 1/22$) is a long-standing puzzle in particle physics
- May be particularly sensitive to new physics because it receives contributions from 1-loop electroweak penguin diagrams



- Lattice calculation of direct CP-violation in K→ππ decays, ε_K', is technically challenging and has not been done for three dynamical quark flavors, so RBC & UKQCD are currently undertaking a major study of K→ππ decay
- Members of BNL high-energy involved in **mentoring Columbia students Q. Liu and M. Lightman** on this project

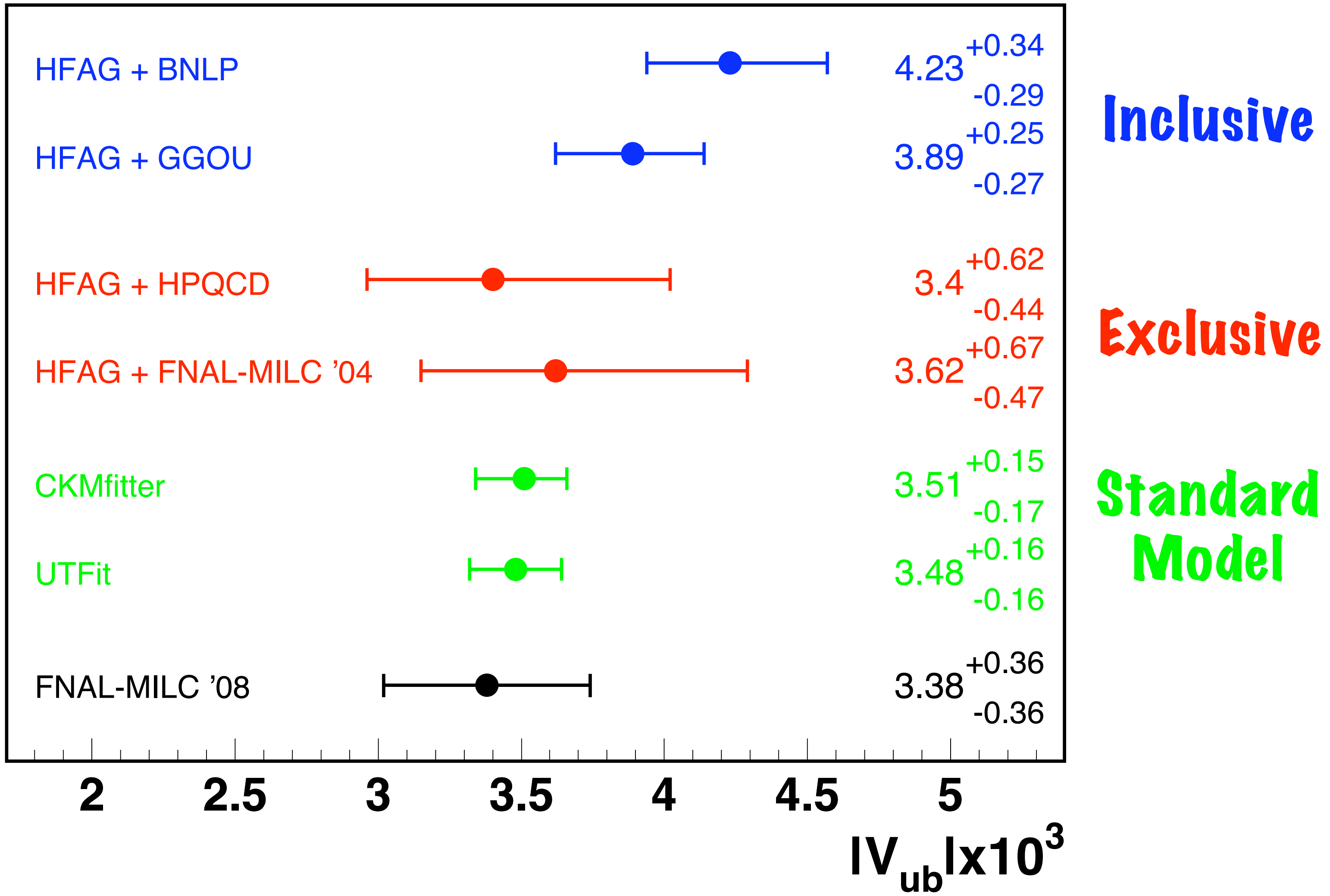
Heavy-quark physics at BNL



The B→$\pi\ell\nu$ form factor (RV for FNAL/MILC)

- Given the experimental branching fraction for B→$\pi\ell\nu$ semileptonic decay, lattice calculations of the hadronic form factor allow a determination of $|V_{ub}|$
- In 2009, the Fermilab Lattice & MILC Collaborations published the best 3-flavor calculation of the B→$\pi l \nu$ semileptonic form factor and exclusive $|V_{ub}|$
- Fitting the BABAR experimental and lattice data simultaneously to a model-independent fit function based on analyticity and crossing symmetry minimized the error in $|V_{ub}|$ (~11% uncertainty)
- Result consistent with previous exclusive determinations, but a 1-2σ tension persists between the inclusive and exclusive determinations

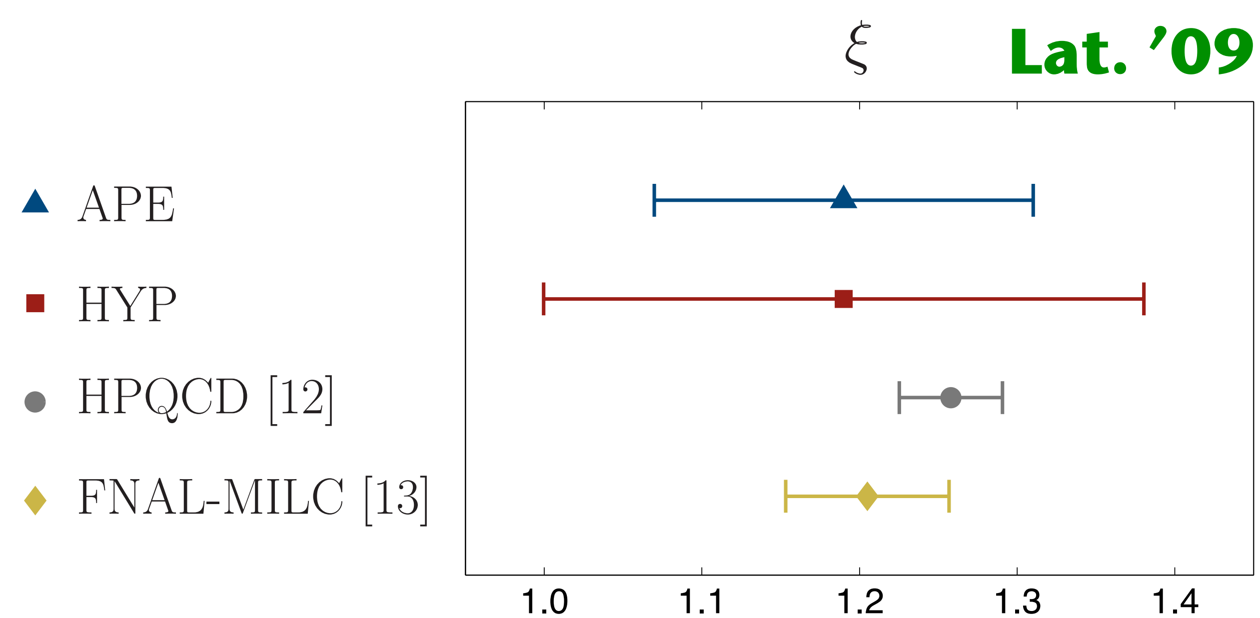
FPCP 2009



Neutral B-meson mixing (RBC/UKQCD)

- Combining the ratio of neutral B-mixing matrix elements (ξ) with exp. measurements of the B_d and B_s oscillation frequencies constrains the apex of the CKM unitarity triangle
- Since the constraint from B-mixing is perpendicular to that from $\sin(2\beta)$, B-mixing plays a key role in searching for new physics in the flavor sector
- Both unquenched lattice calculations of ξ use staggered light quarks, so it is important to have an independent cross-check using different light-quark and b-quark formulations
- We are calculating ξ with domain-wall light quarks and static b-quarks (*publication in preparation*)
  - Will reduce the statistical and systematic errors in a subsequent publication and expect to obtain a competitive final result

O. Witzel Lat. '09



Just the beginning of a larger RBC/UKQCD program in heavy-light physics that will extend to D- and B-meson decay constants and other quantities of interest to CKM phenomenology . . .

Summary and outlook

- Members of the BNL high-energy theory group are computing several of the most important weak-matrix elements for CKM phenomenology
  - Already well-established program in kaon physics has lead to the current best calculations of the $K \to \pi \ell \nu$ form factor and neutral-kaon mixing parameter B_K
  - Now turning our attention to the more challenging target of $K \to \pi\pi$ decay
  - Also beginning a program in heavy-light physics needed to extract CKM matrix elements involving b- and c-quarks
  - Will publish our first heavy-light phenomenology result for neutral B-meson mixing soon

- Although no "smoking gun" of new physics in the flavor sector, there are several hints that one should keep an eye on, such as the tension between the ε_K band and the remaining CKM unitarity triangle constraints

- *Lattice QCD at BNL is poised to play a key role in discovering new physics in the flavor sector!*